Nanostructured optical elements for manipulation of orbital angular momentum

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Abstract—**Applications of glass nanostructuring for manipulation of orbital angular momentum are reviewed. The phase control is implemented via the combination of form birefringence and Pancharatnam-Berry phase.**

Keywords: orbital angular momentum, Pancharatnam-Berry phase

I. INTRODUCTION

Orbital angular momentum (OAM) beams have the unique feature of a helical phase front and have attracted much attention because of the potential applications in telecom, machining and optical manipulation [1]. OAM generation has represented a great challenge as it is often associated to complex and inefficient set-ups.

However, recently a new generation of optical elements has emerged. Instead of relying on phase delay introduced by the material, these components exploit birefringence or dichroism, which due to spatial variation introduces Pancharatnam-Berry phase [2,3]. In order to introduce large birefringence, some sort of surface or bulk nanostructuring is required to induce co-called form birefringence. The nanostructuring can be implemented via photolithography or some self-assembly processes such as laser induced nanograting formation. This not only allows to achieve high retardance values in thin sheets of material but also permits to control local orientation of slow axis. The last feature is extremely important for manipulating phase of optical beams carrying orbital angular momentum (OAM).

Here recent advance in application of self-assembled sub-wavelength structures for manipulating orbital angular momentum will be reviewed and discussed.

II. NANOSTRUCTURING OF SILICA GLASS

One of successful demonstrations of an operating OAM converter exploited curious feature observed in silica glass [4]. Silica glass under exposure of multiple ultrashort laser pulses undergoes a self-assembly process which results in a permanent periodic structure with periods of 200-300 nm. As opposed to surface ripples, nanostructures inside of the material were reported only for only limited number of materials. Recently the evidence of laser-induced self-organization in glasses other than SiO_2 started emerging, including GeO_2 glass [5], binary titanium silicate glass (ULE, Corning) and multicomponent borosilicate glass (AF32 and Borofloat 33, Schott) [6,7]. Germanium dioxide glass and ULE glass, which contains 92 mol.% of SiO_2) possess structure similar to pure SiO_2. However, birefringence in multicomponent glass (AF32) could be achieved only after depositing over 30 000 pulses [7]. This could be related to lower melting temperature of borosilicate glass (working point temperature 1225°C) as compared to fused silica (1800°C). This can also explain the absence of nanogratings in composite glass after the irradiation with high energy (>0.65 μJ) sub-picosecond laser pulses.

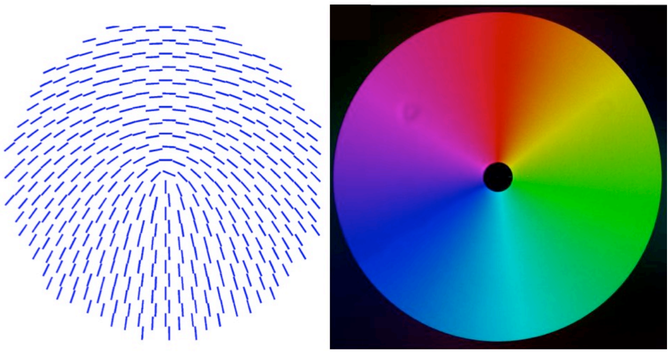

Figure 1. (left) Schematic drawing of nanogratings distribution in a OAM mode converter. The blue dashes indicate the direction of the nanopattern. (right) A fabricated mode converter. The brightness represents the retardance magnitude while the colour indicates the direction of the slow axis

The femtosecond laser written nanostructure acts as a micro-waveplate with slow axis oriented perpendicular to the polarization of the laser beam. Thus the orientation of the structures can be easily controlled by polarization of the writing laser beam. By continuously scanning the bulk of the glass a uniform birefringent layer can be inscribed, which depending on spatial pattern of slow axis can act as a certain optical element, which can control polarization and phase of the passing light (Fig. 1). Using lenses of moderate NA (0.15-0.2) the optical elements with half-wave retardance for ~500 nm can be written in a single scan at a speed of several millimeters per second. The typical thickness of the birefringent layer is less than 100 microns. The half-wave retardance is of particular interest since, when circularly polarized light is transmitted through a half-wave plate an absolute phase shift results, which is equal to twice the rotation angle of the wave plate. Theoretically any phase pattern can be achieved solely by means of geometric phase with efficiencies reaching 100%.

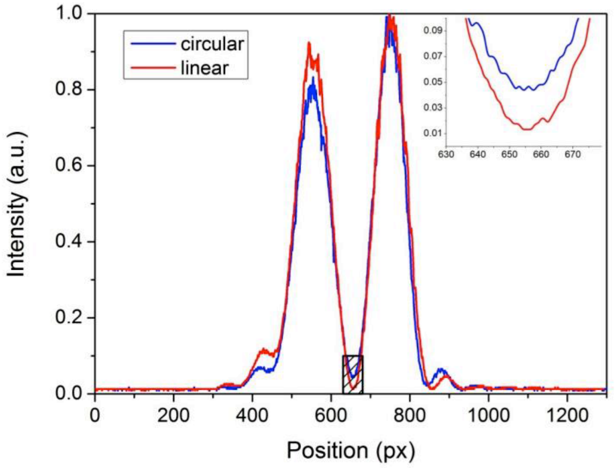

Figure 2. OAM mode contrast after additional filtering (measurements are limited by the dynamic range of the camera). Inset: zoom of the central part.

Surface nanostructuring via lithography allows reaching higher refractive index contrasts and thus producing thinner elements [2]. However, the structure is exposed to the environment and should be handled with extra care. The embedded elements are however encapsulated in the glass, which can be seen as protective layer between the structure and the environment. High melting temperature of the silica glass also contributes to the high thermal stability of the imprinted structures [8].

This approach allowed implementing OAM mode converters for the visible and infrared. The conversion efficiency of these optical elements is limited by optical scattering, which has predominantly Rayleigh dependence. As a result, insertion losses are less than 20% at telecom wavelengths [9]. Another important feature is high damage threshold of these devices, which allows to exploit them for high laser power applications.

As fabrication technique is a direct writing method, it allows implementing optical elements as small as tens of microns. Thus, it can potentially can be integrated into the core of an optical fibre. Recently OAM modes with charge as high as 100 were successfully generated using this approach demonstrating viability of this approach for high order OAM modes [10].

III. MANIPULATION OF ORBITAL ANGULAR MOMENTUM

Important feature of these mode converters is sensitivity of the handedness of circular polarization. Essentially for any state of polarization the mode converter will produce two modes with opposite charge and handedness of circular polarization. The total angular momentum carried by the beam will depend on the ratio of two circular polarizations. This allows obtaining high purity OAM modes after converting a beam into two orthogonal linear polarizations and separating them with a polarizing beam splitter. Experimentally the contrast of OAM mode was improved from 3% (after the mode converter) to >0.1% by additional polarization filtering (Fig. 2).

Additionally, this polarization sensitivity was exploited for controlling angular momentum carried by the laser beam without affecting the intensity distribution This enables to gradually ramp the torque transferred to micro-particles trapped by an optical vortex [11]. By monitoring rotation speed versus applied torque one can analyze the interaction between trapped objects and its environment. Vortices with tunable OAM may allow precise control of particles rotation of any type materials and bio-objects such as DNA molecules measuring not only it is linear but also rotational response of the system.

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